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Development and Testing of a Computer-Assisted Remote-Control System for the Compact Loader-Trammer

By T. M. Ruff

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°F	degree Fahrenheit	mph	mile per hour
ft	foot	ms	millisecond
h	hour	pct	percent
hp	horsepower	s	second
Hz	hertz	st	short ton
in	inch	st/h	short ton per hour
kHz	kilohertz	V	volt
lb	pound	V ac	volt, alternating current
lbf	pound (force)	V dc	volt, direct current
m	meter	W	watt
mA	milliampere	yd^3	cubic yard
MHz	megahertz	yd^3/h	cubic yard per hour
min	minute		

DEVELOPMENT AND TESTING OF A COMPUTER-ASSISTED REMOTE-CONTROL SYSTEM FOR THE COMPACT LOADER-TRAMMER

By T. M. Ruff[1]

ABSTRACT

A prototype mucking machine designed to operate in narrow-vein stopes was developed by Foster-Miller, Inc., Waltham, MA, under contract with the U.S. Bureau of Mines. The machine, called a compact loader-trammer, or minimucker, was designed to replace slusher muckers in narrow-vein underground mines. The minimucker is a six-wheel-drive, skid-steered, load-haul-dump (LHD) machine that loads muck at the front with a novel slide-bucket system and ejects it out the rear so that the machine does not have to be turned around. To correct deficiencies of the tether-remote-control system, a computer-based, radio-remote-control system was retrofitted to the minimucker. Initial tests indicated a need to assist the operator in guiding the machine in narrow stopes. An automatic guidance system that used ultrasonic ranging sensors and a wall-following algorithm was installed. Additional tests in a simulated test stope showed that these changes improved the operation of the minimucker. The design and functions of the minimucker and its computer-based, remote-control system are reviewed, and an ultrasonic-sensor-based guidance system is described.

[1]Electrical engineer, Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

INTRODUCTION

Current methods of mucking narrow stopes involve the use of slushers, overshot loaders, or small load-haul-dump (LHD) units. A safer and more productive means of moving material from the face while working within the physical constraints of a narrow stope has been a popular topic among companies involved in this type of mining. With this goal in mind, Foster-Miller, Inc., Waltham, MA, under contract with the U.S. Bureau of Mines,[2] developed a compact loader-trammer, or minimucker.[3] The minimucker is a six-wheel-drive, skid-steered, LHD machine that can be operated in stopes as narrow as 5 ft. Its unique loading and dumping mechanism allows the machine to tram between an ore pass and a muckpile without turning around. The development of the prototype was completed in 1984, after which the minimucker was sent to the Homestake Mining Co. in Lead, SD, for underground testing.

Following these underground tests, it was decided that a computer-based, radio-remote-control system would allow the operator to remain in a safe location while operating the machine. Such a system would also allow automation techniques to be studied. Using ultrasonic sensors and a simple guidance algorithm, a guidance system was developed that improved the operation of the minimucker by decreasing operator fatigue and machine wear.

ACKNOWLEDGMENTS

The author would like to express his appreciation to Ron Patey, chief engineer, Blackbox Controls Ltd., Glen Williams, Ontario, ON, for his assistance in installing the radio-remote-control system and programming the guidance algorithms.

INITIAL DESIGN AND TESTING

The objective of the contract work done by Foster-Miller was to develop a compact LHD unit to replace the existing methods of mucking narrow stopes in metal-nonmetal mines. The first task was to determine if there was a need for such a machine, after which exact specifications could be determined. The response to a survey of mining operations was positive, and the important parameters for the machine's design were laid out. These parameters included the following:

1. Dimensions should be a maximum of 4.5 ft wide, 7 ft high, and 12 ft long.
2. The average pay load should be 0.75 to 1.25 yd^3.
3. The machine should be powered by air or electricity.
4. The machine should be controlled remotely.

Table 1 lists the exact specifications of the minimucker as determined by the survey, and figure 1 shows the minimucker as originally designed. As seen in the figure, the minimucker uses a slide bucket to load muck onto the loading deck and push it out through the tailgate at the rear of the machine. Because the machine does not have to be turned around to be unloaded, it is ideal for narrow stopes.

Table 1.—Minimucker specifications

Dimensions, in:		
Mucking length		163
Tramming length		152
Mucking height		57
Tramming height		57
Dumping height		61
Width		54
Turning radius	in.	160
Net weight	lb.	7,800
Performance:		
Traction motor output	hp.	2 × 25
Pay load capacity	yd^3.	1-5/8
Rated load capacity	lb.	4,500
Cycle time (200 ft round trip)	min.	2.9
Net hauling capacity	yd^3/h.	32
Do.	st/h.	44
Tramming speed	mph.	3
Breakout force	lbf.	3,000 to 6,000
Electrical system:		
Motor flange (TEFC "D")	hp.	50
Motor flange (3-phase, 60 Hz)	V ac.	460
Lights and solenoids (1-phase, 60 Hz)	V ac.	115
Controls (tethered pendant)	V dc.	12/24

[2]Tallone, T. Compact Loader-Trammer for Underground Metal and Nonmetal Mines. General and Design Review (contract JO205037, Foster-Miller, Inc.) BuMines OFR 10A-86, v. I, 1985, 93 pp.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

A typical mucking cycle requires the following steps: (1) tram to the muck pile, (2) load the minimucker by crowding the pile and retracting the bucket to place the load of muck on the deck (it takes approximately four bucket loads to fill the machine), (3) tram backwards to the dumpsite and position the tailgate over the ore pass, (4) open the tailgate and retract the bucket fully until all the muck is ejected, and (5) close the tailgate and lower the bucket to repeat the cycle.

On the original system, the operator used a control pendant that was physically connected to the machine by a 30-ft-long multiconductor tether. This required the operator to follow the machine during the mucking process and to keep the tether from being run over during machine operations.

With the cooperation of Homestake Mining Co., Bureau researchers conducted an underground test when the prototype minimucker was completed. At the testsite, the machine shuttled waste to a 5-ft-diam borehole 20 ft from the waste pile. Approximately 75 st was moved. The following difficulties were noted by one of Homestake's mining engineers:

1. The channel-and-roller power cable festoon system recommended in the contract report could not be used because it was difficult to install and because it was susceptible to damage from nearby blasting.
2. The bucket was not very efficient during digging because of its straight leading edge.
3. Bucket cycle speeds were slow because of the slow speed of the three-stage telescopic cylinders.
4. The tether remote control made operation awkward and, in some situations, unsafe.

The only modification made after the initial test was to redesign the bucket. This included changing the shape of the leading edge of the bucket and improving the mechanism for holding the bucket against the machine body while digging. Following these changes, a second test was run in which 125 st of waste was moved. The bucket redesign improved digging efficiencies. However, modifications were still needed to improve the speed of bucket movement and so the three-stage telescopic cylinders used for bucket movement were replaced by a chain-actuated, single-stage-cylinder slide mechanism (fig. 2). Although loading times were projected to be half the original times, Homestake was not able to resume testing after this modification.

The overall results from these preliminary tests were promising. Noted advantages included the following:

1. The minimucker was easy to maneuver because of its small turning radius.
2. Overall dimensions allowed the minimucker to fit into any area of the mine and made interlevel relocation simple.
3. The machine had powerful crowding capabilities for loading muck.
4. The modified bucket improved cycling times.

Disadvantages included the following:

1. The machine was unable to load ore cars.
2. The low dump gate clearance made maneuvering over the dump point difficult.
3. The tether remote control still made operation cumbersome and unsafe.

The minimucker was delivered to the Bureau's Spokane Research Center (SRC) in 1988. After reviewing the underground test results and operating the machine at SRC, project personnel determined two ways in which the minimucker could be improved: eliminate the need for the tether cable and incorporate computer-based technology into the control system.

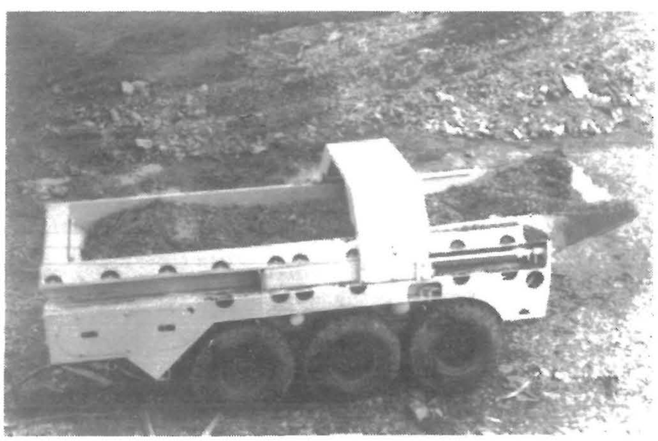

Figure 1.—Minimucker as originally designed.

Figure 2.—Minimucker with bucket and slide mechanism modifications.

COMPUTER-BASED, RADIO-REMOTE-CONTROL SYSTEM

To eliminate the need for a tether in remote-control operations, both infrared remote control and radio-frequency remote control were considered. Infrared remote control was eliminated as an option in this situation because of its susceptibility to interference from heavy dust and because the operator has to be within the line of sight of the machine. While radio-remote-control systems are more costly than infrared control systems, they are not susceptible to interference from dust. Also, radio-remote-control communications are omnidirectional and while they do have some line-of-sight restrictions, the placement of the transmitter and the receiver is not as critical.

Recent developments in computer-based, radio-remote controls allowed the needed improvements to be implemented with one system. Programmable, computer-based radio control systems developed by Blackbox Controls, Ltd.,[4] had been installed on LHD's in several mines in the United States, so this system was chosen to be retrofitted to the minimucker. The system consisted of a control pendant and transmitter, receiver, microprocessor, and control electronics (figs. 3-4). Rather than the control outputs being connected directly to the servovalves and other machine devices, the radio control system interfaced with the electronics originally used for the tether-remote-control operation. This simplified installation and allowed the option of using either radio-remote or tether-remote control.

TRANSMITTER

The system's transmitter is located within the control pendant. Commands that can be sent include motor on and off, open and close tailgate, raise and lower bucket, set and release brakes, turn rear and front lights on and off, learn and repeat, and tram forward, reverse, left, or right. Radio transmissions of command signals are sent out in 15-ms bursts, and the radio transmitter is turned on only for the time of the transmission. Idle time varies between 240 and 50 ms, depending on the amount of activity of the controls. This discontinuous transmission has the advantage of prolonging the transmitter's battery life.

Along with the control command signals, a code unique to the system on each machine is transmitted; this feature allows the same radio frequency to be used by more than one machine. The modulation scheme uses narrow-band FM, pulse width modulation at 450 to 470 MHz and is transmitted at 0.2 to 0.4 W. The transmitter requires a 12-V, nickel-cadmium rechargeable battery. If transmissions stop or become blocked or if the pendant is tilted over 40° off vertical, the minimucker shuts off and the brakes are set.

RECEIVER

The receiver portion of the system is located on the exterior of the minimucker in a steel enclosure. A 6-in monopole, whip-type antenna is also mounted on the exterior of the machine. Commands received from the transmitter initiate software routines that execute the desired function. All functions are controlled by relay or on-off switches except the tramming controls, which are proportional. The tramming outputs from the radio receiver are intended to drive electrohydraulic controls directly. However, since the output is interfaced to the original control electronics, isolated proportional potentiometers are required to convert the pulse width modulated

[4]Blackbox Controls, Ltd. (Glen Williams, Ontario, ON). Operations and Maintenance Manual for IQ Series Remote Controls. 1989, 35 pp.

Figure 3.—Components of radio-remote-control system: relay enclosure, computer and receiver, power supply enclosure.

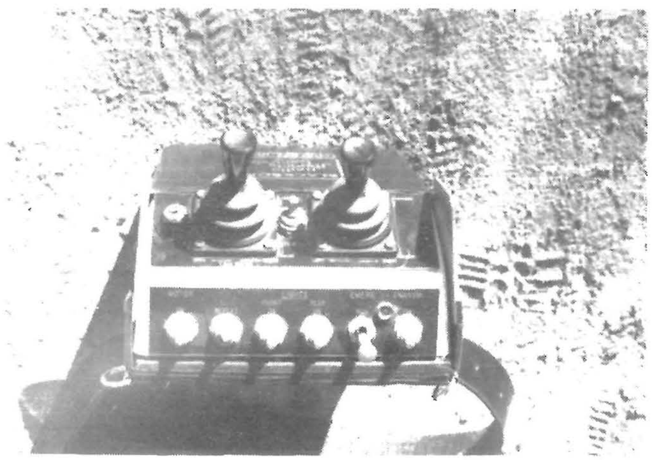

Figure 4.—Remote-control pendant.

input from the radio transmitter to a signal that simulates the potentiometer system used in the original tramming controls. Thus, movements of the tramming joystick allow the operator to increase or decrease the speed of the minimucker in proportion to the amount of deflection of the joystick.

COMPUTER SYSTEM

The computer portion of the remote-control system consists of an INTEL 8031 microprocessor and removable battery SRAM modules that contain the operations programs. A command transmitted from the control pendant initiates the portion of the software that controls the function for that command. For example, moving the tramming joystick forward at half full scale would initiate a program that controls the servovalves that govern forward movement of the minimucker. The half full-scale deflection corresponds to a variable gain value set within the program that corresponds to the joystick position transmitted, causing the minimucker to travel at half of full speed.

This system is similar to a programmable controller and allows customized programs and sensor input to be used in the control of the minimucker. To enter customized programs or modify existing ones, a personal computer or dumb terminal can be connected using serial (RS232) communication.

Along with customized programs, a learn-and-repeat mode allows automation concepts to be tested. That is, the minimucker can be "taught" to execute a series of commands automatically by memorizing the commands in "learn" mode. Memorization is accomplished by going through the steps of the operation one at a time. After these commands have been stored by the microprocessor, depressing the repeat switch on the control pendant causes the minimucker to repeat the commands. This can be useful in decreasing the time required to execute a simple repetitive action that would normally take several separate commands to achieve—for instance, unloading the minimucker. However, the learn-and-repeat system is time based and unintelligent. For instance, the system memorizes the amount of time the output for the "raise bucket" command was on. When the repeat system is activated, the bucket is raised for the memorized amount of time whether the bucket is at the end of its travel or not. Feedback from sensors indicating the position of the bucket can be added to make the system position-based.

TEST SETUP AND RESULTS

Full-cycle tests were conducted to evaluate the radio-remote-control system and bucket modifications on the minimucker. A simulated stope 6 ft wide by 100 ft long was constructed of reinforced concrete to represent a narrow drift with a muckpile and an ore pass. A festoon system for handling the power cable was also constructed from 3/8-in-diam wire rope suspended between two posts across the entire 100-ft length of the simulated stope. The power cable was connected to pulleys suspended from the wire rope, which allowed the pulleys to roll as the minimucker pulled the power cable. Figures 5 and 6 show the simulated stope and festoon system.

The cycling tests involved running the minimucker through a complete mucking cycle while all operations of the cycle were timed. The operator of the minimucker stood behind the dumping bin with a maximum distance of 125 ft between him or her and the machine. Four hours of continuous mucking were monitored. The tests showed that the load, haul, dump, and return cycle took an average of 2.2 min, and with an average load of 1.6 yd^3, the minimucker could haul an estimated 59 st/h. Tests of the original minimucker, as described in the contract report, showed a cycle time of 2.9 min and a capacity of 44 st/h (table 1). These original tests were conducted under similar conditions and with a 100-ft tramming distance, but were not conducted in the simulated stope.

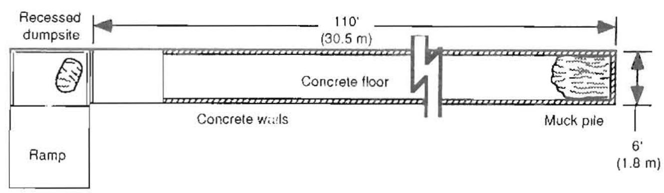

Figure 5.—Test stope layout.

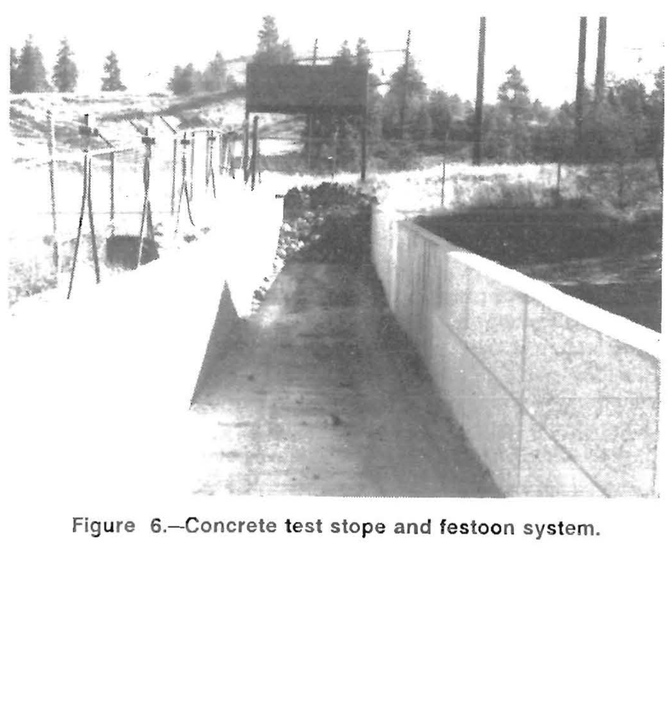

Figure 6.—Concrete test stope and festoon system.

Tests in the simulated stope also showed that the operators became extremely fatigued as they attempted to keep the minimucker from hitting the stope walls. Because avoiding collisions was impossible, machine wear was also excessive. It was evident that some type of assistance was needed to guide the minimucker through the stope. Collision avoidance would become even more critical in a dark, underground environment.

AUTOMATIC GUIDANCE SYSTEM

SENSOR SELECTION

Several different options for automatic guidance were evaluated, including the use of ultrasonic ranging sensors, wires embedded in the stope floor, and optical path following. Ultrasonic ranging was chosen for the following reasons: (1) The tramming path of the minimucker in a narrow stope was seen as relatively simple; that is, the minimucker had only one possible tramming path, which would be relatively straight with no complex turns or direction changes, (2) in a narrow stope, the walls would be close to the machine and would be, in most situations, continuous, (3) the costs of using ultrasonic ranging sensors and the existing computer system were much cheaper than costs of the other alternatives, and (4) the sensory system could be totally contained on the minimucker so that no additional preparation in the stope would be required.

The ultrasonic ranging sensors needed to be small to fit on the machine, but they only needed to measure short distances (under 3 ft), making them relatively inexpensive. At the same time, they had to be rugged and waterproof. The sensors finally chosen were selected because of their low cost, small size, ruggedness, water resistance, and availability. Specifications of the sensors used are shown in table 2.

Table 2.—Agastat ultrasonic sensor specifications

Dimensions, in:	
Diameter	1.2
Length	2.8
Input voltage . . . V dc. .	10 to 30
Maximum current drain . . . mA. .	50
Output, V dc:	
Minimum distance	0
Maximum distance	5
Operating frequency . . . kHz. .	210
Beam width . . . deg. .	10
Sensing distance . . . in. .	4 to 30
Response speed . . . ms.	50
Temperature rating . . . °F. .	-40 to 122
Humidity . . . pct. .	0 to 95
Waterproof enclosure	([1])
Cost (approximate)	$260

[1]Front transmitting surface must be dried before operation.

ORIGINAL SYSTEM OPERATION

One ultrasonic ranging sensor was mounted on each of the four corners of the minimucker. A 0- to 5-V analog signal is sent to an onboard computer, where it is digitized. This signal is proportional to the distance between the sensor and the stope wall. Figure 7 shows a sensor mounted in a protective case and bolted to the minimucker frame. Figure 8 shows the layout of the sensors. When the machine is tramming forward, the outputs from the front left (V_{LF}) and right (V_{RF}) sensors are used; when tramming in reverse, the outputs from the rear left (V_{LR}) and right (V_{RR}) sensors are used.

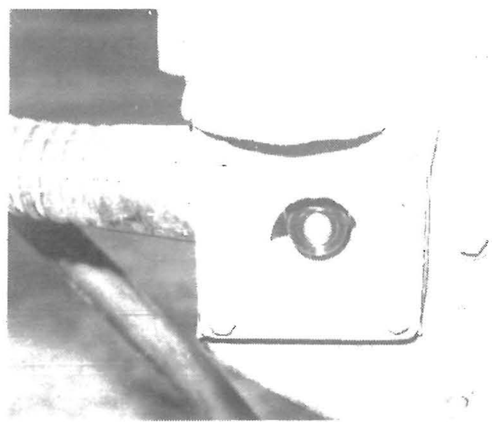

Figure 7.—Ultrasonic ranging sensor mounted on minimucker.

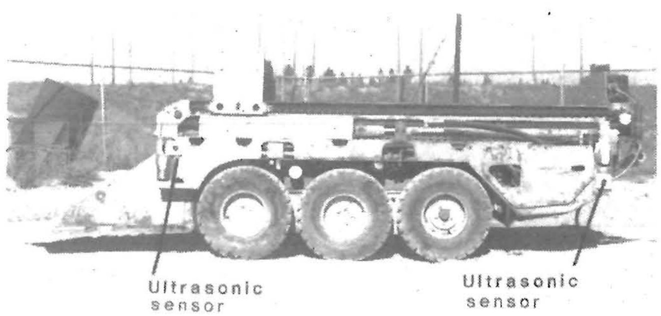

Figure 8.—Sensor layout.

The computer scans the appropriate pair of sensors 10 times per second. After the signals are digitized, the binary values are complemented so that small voltages relating to close distances to the wall result in large hexadecimal values. To correct the machine's position, values from the left and right sensors are subtracted from one another, resulting in zero if the machine is in the center of the stope or in a negative or positive nonzero value (ΔV) if the machine is not centered in the stope (fig. 9). If the resulting signal is nonzero, the computer corrects the machine's position by causing the right or left drive motor to slow down momentarily, steering the machine away from the wall until the signal is once again zero. The amount the machine is turned is determined by the magnitude of the resulting subtracted value.

Operation of the guidance system is controlled with the existing pendant. A switch turns the automatic guidance system on or off. When on, pushing the tramming control full forward or full reverse causes the minimucker to move forward or reverse at full speed while the guidance system automatically corrects the machine's path to keep it away from the walls. The guidance system only affects tramming and does not alter the operation of the other manual controls. The automatic guidance system can be turned off when muck is being cleaned up next to the walls; otherwise, the system can be left on, and loading and dumping can continue as described in the section "Initial Design and Testing."

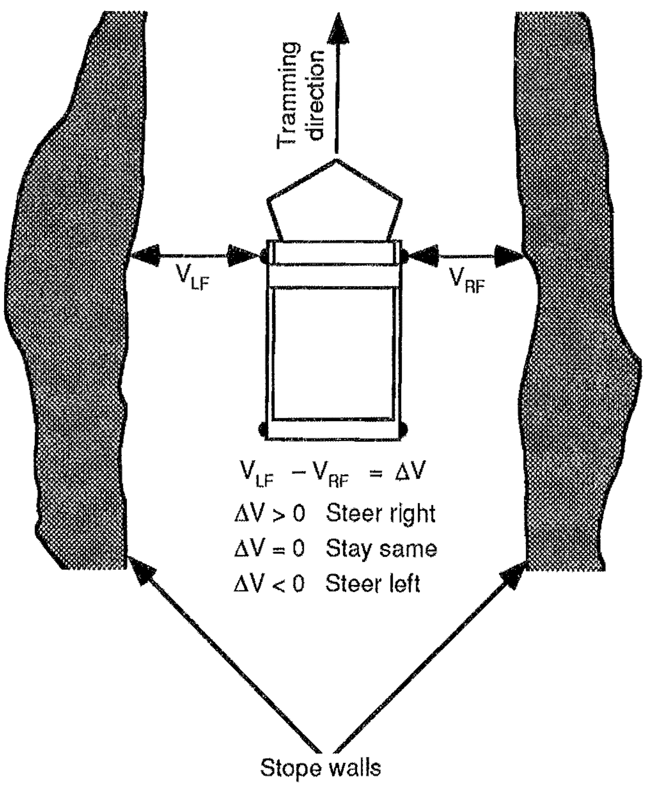

Figure 9.—Original guidance system operation.

TESTING ORIGINAL GUIDANCE SYSTEM

One concern with ultrasonic sensors was that accurate operation depends on the surface that is reflecting the sound waves. Optimum conditions require that the reflecting surface be flat and perpendicular to the incident sound waves. Smooth, flat surfaces at angles close to 45° relative to the sound waves will reflect the waves away from the sensors so that the sensors detect no object in the sensing zone. However, the concrete walls of the test stope (and walls in a mine) are not perfectly smooth. Bumps and depressions provide enough surface area to reflect at least a portion of the sound waves so that accurate measurements can be made.[5]

To test the effect of large irregularities in the simulated stope walls, a portion of the concrete wall was lined with corrugated steel; after the cement dried, the steel was removed, leaving a wavelike pattern in the wall. These irregularities did not adversely affect the accuracy of the sensors.

Several mucking cycles were run in which the gain of the steering correction was altered to optimize the reaction speed of the minimucker. These preliminary tests showed that the effort required to keep the minimucker from hitting the stope walls decreased. The machine traveled at full speed (3 mph) in both forward and reverse for the 100-ft length of the stope and at the same time corrected its position so that it remained in the center.

In doing this, however, the minimucker's tramming path oscillated from one side of the stope to the other (fig. 10). In some instances, the oscillations became too large and occurred too frequently, and the machine could not correct its position fast enough to avoid colliding with the wall. Additional tests showed that the oscillations resulted from the combined effects of two characteristics of the algorithm. First, the algorithm adjusted the position of the minimucker using the monitored distance from both walls. If the machine was tramming at a position in the stope where it was an adequate distance from the walls, it would still correct its position so that it would be centered in the stope. This caused the minimucker to correct its position constantly even if it was following a safe path. Second, when correcting the path, the algorithm sent a signal to one drive motor to slow down so that the minimucker would turn away from the wall. The minimucker would then head for the other wall, a problem inherent with skid steering.

[5]King, R. H., P. J. A. Lever, W. Strickland, and J. D. Lane. Ultrasonic Rangers for Underground Mine Equipment Navigation. Paper in Proceedings of the 1st International Symposium on Mine Mechanization and Automation (Golden, CO, June 10-13, 1991). CO Sch. Mines, Golden, CO. V. 1, 1991, pp. 6-31 to 6-44.

Another problem involved cutouts within the stope. To simulate a cutout or void in the stope wall, a piece of foam rubber approximately 5 ft wide, 4 ft high, and 2 in thick was placed against the inside of one of the stope walls about midway between the muckpile and dumping bin. The foam rubber absorbed enough of the sound waves transmitted by the sensors to simulate the absence of a wall. In the tests, the minimucker stayed near the center of the stope until it encountered the perceived void in the wall, at which point it tried to center itself between the wall and the void (fig. 11). Because it could not correct itself in time, it collided with the wall where the foam rubber ended.

After testing several different guidance schemes, researchers determined that this problem could not be corrected with the existing system and would require additional forward- and reverse-looking sensors that would recognize a large void in the stope wall. Figure 12 shows one possible sensor layout. This system will be the subject of later work and was not addressed in the algorithms discussed in the following section.

A third problem was that the steering reaction speed depended on hydraulic fluid temperature. Much of the work done in the test stope was done during cold weather when temperatures were around 40° F. As the minimucker warmed up, the operation of the system improved, but if the machine was run in the automatic guidance mode while it was cold, the system was unreliable. This problem was solved by allowing the minimucker to warm up for 30 min before testing began. In most underground environments, cold temperatures would not be a problem.

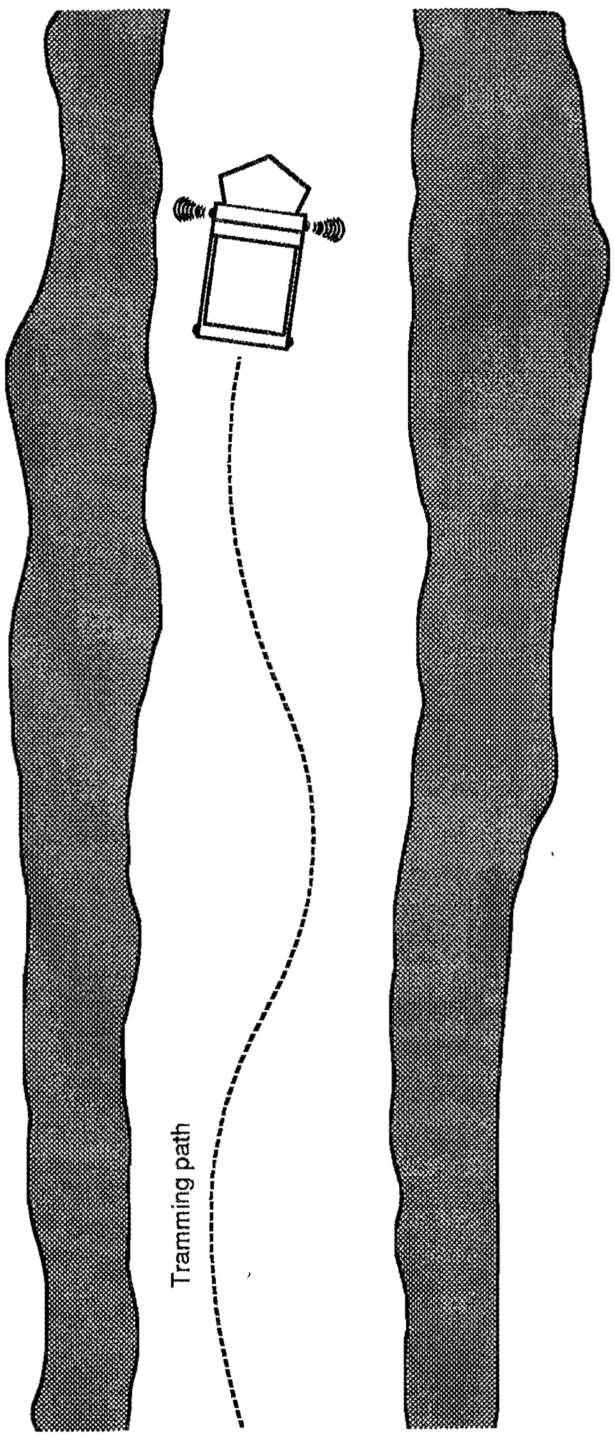

Figure 10.—Oscillations in tramming path.

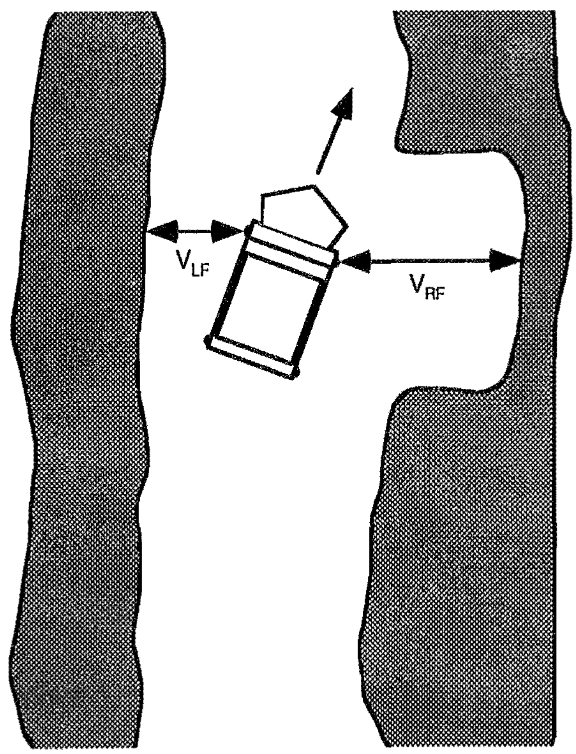

Figure 11.—Centering at cutout.

ALTERNATE ALGORITHM

The test results indicated that the algorithm should be modified to dampen, if not eliminate, the path oscillations. Several solutions were studied, including limiting the sensing distance of the ultrasonic sensors to 8 in so that the minimucker would base its path corrections on its distance from one wall at a time and also correct its steering according to distances measured simultaneously at the front and rear of the machine.

The first attempt to dampen the oscillations in the tramming path involved limiting the sensing distance of the ultrasonic sensors to 8 in so that objects outside of this 8-in zone did not affect the sensor output (fig. 13). However, this modification alone did not correct the problems satisfactorily because this distance did not allow enough time for the minimucker to correct its position, resulting in collisions with the wall. Also, because only the front sensors were used in forward travel, when the machine was close to the wall, large corrections caused the front to move away from the wall but the rear to collide with the wall. When tramming in reverse, the reaction was the same but at opposite ends.

To correct the problem and dampen oscillations in the tramming path, information from all the sensors was used simultaneously. When tramming forward, the front sensors were monitored and the computer program determined which wall was closest to the minimucker. This determined which rear sensor was used to set the amount that the minimucker should turn. For example, if the minimucker was traveling forward, close to the left-hand wall (fig. 14), the guidance software would subtract the value from the right front sensor, V_{RF}, from the value of the left front sensor, V_{LF}. All these values would be complemented so that small voltage signals relating to the proximity of the sensors to the wall would be converted to large hexadecimal values. V_{LF} would then be subtracted from the value of V_{LR}, and this value

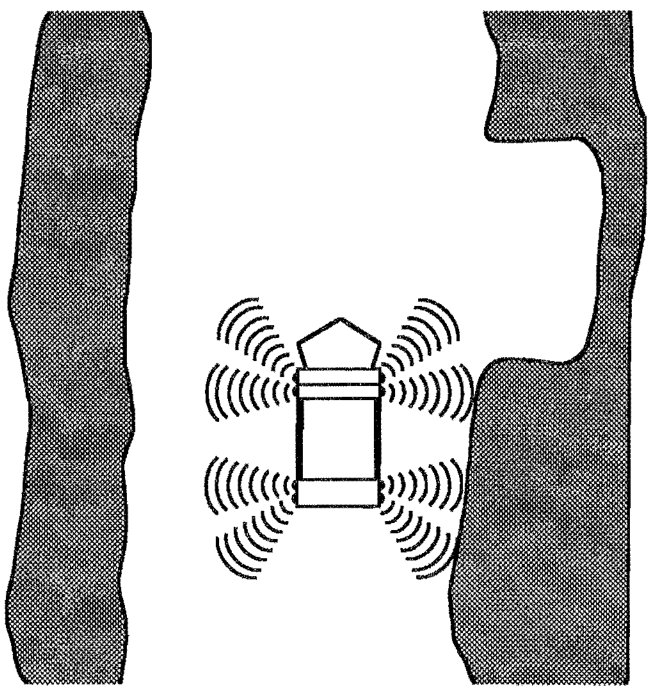

Figure 12.—Addition of forward- and reverse-looking sensors to recognize cutouts.

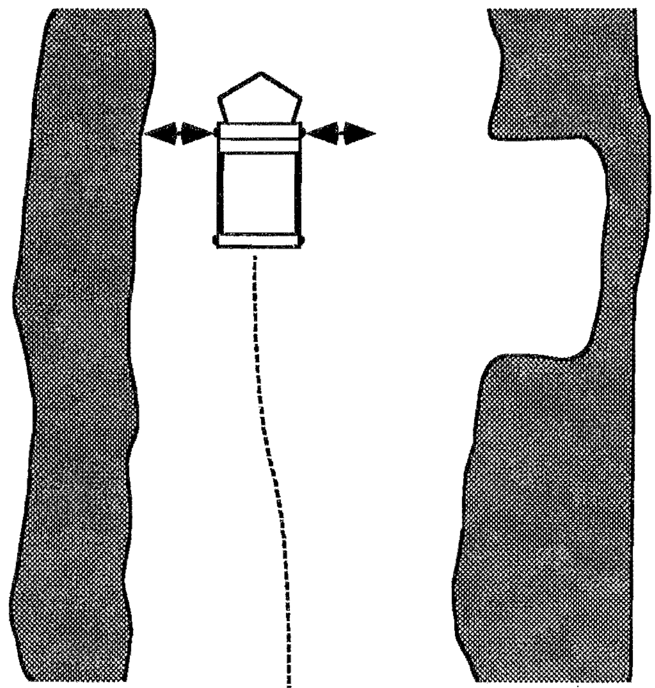

Figure 13.—Limiting sensing distance.

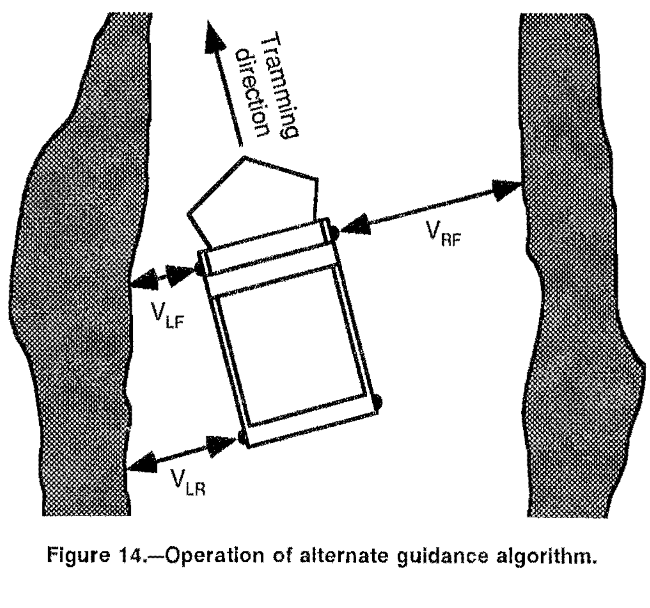

Figure 14.—Operation of alternate guidance algorithm.

would be multiplied by a software adjustable constant, K. These two values would then be subtracted, resulting in the correction factor that controlled the amount the machine turned away from the wall. Thus,

$$G = (V_{LF} - V_{RF}) - K(V_{LR} - V_{LF}),$$

where G = path correction gain.

If the front of the machine was closer to the wall than the rear, $(V_{LR} - V_{LF}) < 0$, then the second term of the equation would be multiplied by K and the steering correction would be increased. If the rear of the machine was closer to the wall, $(V_{LR} - V_{LF}) > 0$, then the machine would already be correcting its position and the second term would be ignored. Similar but opposite operations would take place when the machine was tramming in reverse.

The new algorithm was tested by operating the minimucker in the simulated stope. Several values of K were tried; a value of 2.0 gave the best results. Oscillations in the tramming path were dampened with this version and tramming was greatly improved—there were no collisions with the wall. During cycling tests, no large improvements were seen in hauling capacity. However, machine wear was greatly reduced because collisions with the stope walls were avoided and the machine could be controlled easily in the narrow confines of the stope, which made the tramming portion of the mucking cycle essentially effortless.

SUMMARY

The minimucker shows potential as an alternative machine for mucking narrow stopes. Tether remote control that requires the operator to follow the machine is not acceptable for long tramming distances, so a wireless method of directing the equipment is required. A radio-remote-control system was recommended for controlling this machine in narrow stopes. However, because of the difficulty in maneuvering a rubber-tired vehicle in a narrow stope, some type of assistance was needed to keep the machine from hitting the stope walls.

Computer-assisted guidance using ultrasonic ranging sensors was implemented using the computer and controls of a radio-remote-control system. A simple algorithm was tested that allowed the minimucker to follow the walls of the stope while avoiding collisions. The first attempt used only two of the four sensors to monitor the minimucker's distance from the walls. Oscillations in the tramming path made this algorithm unacceptable. The operation of the guidance system was improved by using all four sensors to determine position and control the minimucker. While this modification dampened path oscillations, it did not solve the problem of wall collisions when large voids or cutouts in the stope walls were passed. Solving this problem may require additional sensors and may be the focus of later work. Although the automatic guidance system did not significantly improve mucking cycle times for continuous mucking over a 2-h period, the system did reduce machine wear and operator fatigue, making long periods of mucking more productive when considering ergonomics and maintenance.

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